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PLATE TECTONICS ON VENUS

Don L. Anderson

Seismological Laboratory, California Institute of Technology

Pasadena, California 91125

Abstract. The high surface temperature of Venus implies a permanently buoyant lithosphere and a thick basaltic crust. Terrestrial style tectonics with deep subduction and crustal recycling is not possible. Overthickened basaltic crust partially melts instead of converting to eclogite. Because mantle magmas do not have convenient access to the surface the ^{40}Ar abundance in the atmosphere should be low. Venus may provide an analog to Archean tectonics on the Earth.

Introduction

The surface of Venus is about 450 K warmer than the surface of the Earth. This affects the buoyancy, thermal expansion, thermal conductivity and, hence, the thermal evolution and ultimate fate of the lithosphere. The pressure in the upper mantle of Venus is at least 12% less than at equivalent depths in the Earth's upper mantle. Thus, the depth of melting, the locations of upper mantle phase changes and the viscosity of the upper mantle will be different for the two planets. The buoyancy and thermal properties of the lithosphere control the style of plate tectonics and the associated time and length scales. Most discussions of the comparative tectonics between Earth and Venus address only the differences in viscosity.

The oceanic lithosphere of the Earth cools as it ages and it eventually becomes denser than the underlying mantle. This instability develops after about 40 m.y. (Oxburgh and Paramentier, 1977). Once cooling reaches a depth of 50 km the garnet pyroxenite or eclogite transformations may make a substantial contribution to the negative buoyancy of the lithosphere. Continents and oceanic plateaus resist subduction because of their thick low-density crusts. The fate of the terrestrial lithosphere, therefore, depends on both chemistry and temperature. The purpose of this paper is to investigate the implications for Venus tectonics of its high surface temperature. We will conclude that the surface thermal boundary on Venus is permanently buoyant and that the reversible part of mantle convection occurs below about 100 km.

Lithospheric Cooling

If we assume that the temperatures under ridges are nearly isothermal at 1320°C then the average temperature of the oceanic lithosphere decreases about 660°C as it ages. The thickness of the conductively cooled thermal boundary layer increases at a rate controlled by the thermal conductivity and the difference between the surface and interior temperatures. Since the crustal and harzburgite portions of the boundary layer are both less dense than the underlying mantle a gravitational instability can only occur after the conductive cooling penetrates for a sufficient distance, ~30 km, into the denser upper mantle portion of the boundary layer. In some petrological models the lower lithosphere is pyroxenitic. Upon cooling, plagioclase and spinel pyroxenite convert to garnet pyroxenite or eclogite with a substantial increase in density. These phase changes also also require cooling to depths in excess of 30 kilometers.

The maximum thickness, δ, of the thermal lithosphere is

$$\delta = K\Delta T/\dot{Q} \qquad (1)$$

where K is the thermal conductivity, $\Delta T/\delta$ is the average thermal gradient and $\dot{Q}$ is the mantle heat flow. For K of 7×10^{-3} cal/cm sec°C, ΔT of 1300°C and Q of 0.6 μcal/cm^{2}sec, values which may be appropriate for the terrestrial oceanic lithosphere, δ is about 150 km. For a lithosphere composed of 6 km of basalt, 24 km of harzburgite and a lower lithosphere composed of undepleted mantle, the equilibrium boundary layer for ΔT = 1300°C is 1% denser than underlying mantle and therefore gravitationally unstable. Phase changes in the lower lithosphere may contribute further to the negative buoyancy.

The deep interior temperatures of Venus should be about the same as the Earth's if the mantle heat flow is the same. For a given mantle temperature and mantle heat flow the equilibrium thickness of the boundary layer on Venus is reduced by two effects; K is about 30% lower at the higher temperature (Schatz and Simmons, 1972) and ΔT is reduced by 460°C. This reduces δ on Venus to 42 km and its density, assuming similarity with oceanic lithosphere, is 2% lighter than the underlying mantle. This is a result of the smaller amount of cooling, the higher proportion of basalt and harzburgite in the boundary layer and the lack of significant cooling where it is most required, i.e. the lower lithosphere. Furthermore, phase transformations in the lower lithosphere cannot contribute at high temperature and low pressure. Basalt has about one-half the thermal conductivity of ultramafic rocks. This reduces the thickness of the boundary layer to about 27 km if it is mainly basaltic.

The buoyancy of the Venus lithosphere, even for a relatively thin crust, is greater than the buoyancy of young oceanic lithosphere on Earth. Since a thicker crust for Venus is probable, it is certain that the surface thermal boundary layer for Venus is permanently buoyant and stable against subduction. Variations in

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elevation and gravity should reflect variations in crustal thickness and lateral temperature variations.

The temperature gradient in the conductive layer can be written

$$dT/dz = (1/K)(\dot{Q}_s - Az) \quad (2)$$

where $\dot{Q}_s$ is the surface heat flow, z is depth and A is the heat production rate in the layer. With basaltic conductivities and radioactivities ($A \sim 10^{-14}$ cal/cm^3 sec) the temperature and thermal gradient at 20 km are 950°C and 23°C/km respectively and the solidus of dry basalt will be exceeded at depths shallower than 40 km. Eclogite is not stable in the mantle of Vanus at depths shallower than about 100 km (Anderson, 1980).

Since crust cannot subduct and the garnet-rich assemblages are well below the boundary layer, all partial melt products of mantle differentiation that make their way into the outer 100 km or so will remain there. The crust is therefore likely to be thicker than either the oceanic crust or the average crustal thickness on Earth. It may be thicker than either the mechanical lithosphere or the thermal boundary layer. Crust which is overthickened by compression, buckling, thrusting, or collision will melt at its base. The resulting plutonism will further increase the density contrast between crust and mantle and increase the radioactivity and incompatible trace element content of the parts of the crust so affected.

The characteristic time for thickening of the boundary layer is

$$\tau = (\rho C_p/4\ K)\delta^2 \quad (3)$$

which for $\rho = 3.3$ g/cm^3, $C_p = 0.25$ cal/g°C and $\delta = 150$ km is $\sim$ 200 m.y. for the Earth. For Venus the characteristic time is 20 m.y. or less.

Therefore, Venus has a thick, low-density and permanently buoyant crust-lithosphere that very quickly reaches thermal equilibrium. Upper mantle temperatures are, on the average, higher than in the Earth, resulting in low viscosities.

The basalt-eclogite transformation will occur below about 100 km. The driving mechanism for mantle convection may therefore be partly chemical. Basaltic melt rising in an upcurrent will freeze as eclogite if it remains below about 100 km, and provide the negative buoyancy required for overturn. The 670 km discontinuity which halts eclogite subduction on Earth (Anderson, 1979a,c) will occur at about 800 km in Venus giving a convecting layer about 700 km thick. This should generate topographic and gravity anomalies of about 1400 km wavelength.

Equation (1) suggests that tectonics in the Archean on Earth may have been similar to present day tectonics on Venus. The small δ in early Earth history was primarily due to the high $\dot{Q}$, from radioactive decay, which was at least three times larger 4×10^9 years ago. The thermal boundary layer thickens as $\dot{Q}$ decreases until eventually it becomes unstable and overturns, destroying the early geological record and setting the stage for the present style of tectonics (Anderson, 1979a,b, 1980). This overturn event would allow much of the accumulated ^{40}Ar in the upper mantle to escape and the subsequent steady-state ridge/trench style of tectonics allows continuous outgassing of the terrestrial mantle. The actual thickness at which the thermal lithosphere becomes unstable depends on whether the lower lithosphere is harzburgite or garnet pyroxenite.

Early Evolution of Earth and Venus

The initial evolution of Earth and Venus were likely quite similar. The high accretional energies would result in partial melting of the mantle and upward transport of a picritic melt. Crystallization of this upper mantle melt layer, or magma ocean, yields a thin plagioclase-rich crust and a deep eclogite cumulate layer. An olivine-orthopyroxene cumulate layer may form at intermediate depths. This kind of scenerio is well documented for the Moon except that pressures are too low for extensive eclogite fractionation. Eclogite fractionation removes Al_2O_3 from the melt and reduces the thickness of an early anorthositic crust. Eclogite cumulates sink no deeper than 670 km on Earth because of the intervention of the ilmenite and perovskite phase changes in a peridotitic mantle (Anderson, 1979c). An eclogite cumulate layer will be deeper and smaller in Venus because of the effect of temperature and pressure on the phase boundaries and the limited stability field of eclogite in the upper mantle. Nevertheless, the early tectonics, geochemical differentiation and outgassing of the two planets were likely to have been similar.

If the outer layer becomes unstable as the planet cools, the situation changes. Subducted slabs affect both the flow and thermal regime of the upper mantle. The sinking of the cold boundary layer deep into the upper mantle drags cold isotherms to depth and allows hot replacement material to rise at ridges. This leads to relatively large lateral and vertical temperature differences in the upper mantle and rapid convection in which the surface boundary layer participates.

The mantle of the Earth contains approximately 15-20% of a basaltic component. If the mantle were well differentiated this would give a crustal layer 350-450 km in thickness. Only the top 50 km would be buoyant, because of the eclogite transformation, but this is still more than 4 times the present average crustal thickness. The lunar and Martian crusts are much closer to being the appropriate thickness for a well differentiated planet in spite of the fact that accretional heating must have been less for these bodies. The difference, of course, is due to the continuous removal of basaltic crust from the surface implying a long-term storage reservoir at depth. The size of this reservoir has been estimated to represent about 20% of the mantle (Anderson, 1980).

Samples thought to be representative of the upper mantle are depleted in Al_2O_3, CaO and SiO_2 compared to cosmochemical estimates of mantle composition. They are also depleted in trace elements which are retained by the eclogite minerals, garnet and clinopyroxene. The degree of depletion implies an eclogite layer about 450 km thick which is probably deeper than 200 km.

The ^{40}Ar abundance for Venus is about an order of magnitude less than for the Earth (Pollack and Black, 1979). This suggests that late outgassing has been less efficient for Venus than for the Earth in spite of the higher surface and upper mantle temperatures. This is easily understood with the present model. On Venus, mantle melts and their volatiles mainly have access to the surface through relatively transient rifts. Because of the conservation of near surface material these rifts can only form when the crust compresses or thickens somewhere else on the planet. The amount of early outgassing on the two planets may have been similar but Venus did not experience the early lithospheric overturn event or the outgassing associated with continuous crustal renewal at ridge axes.

Conclusions

The high surface temperature of Venus has several important tectonic implications. The most significant is the small amount of cooling that the lithosphere experiences before it reaches thermal steady-state. This increases its buoyancy and long-term stability at the surface when compared with the terrestrial oceanic lithosphere. Since crust cannot be recycled into the mantle the thickness of the basaltic crust on Venus is much greater than on Earth. The combination of a thick crust and high temperatures decreases the thermal conductivity of the lithosphere. This means that for a given mantle heat flow the temperature gradient in the lithosphere is greater than would be the case for a cold lithosphere with a thin crust. This leads to high upper mantle temperatures, low viscosities and the possibility of partial melting at relatively shallow depths.

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